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Sociomaterial movements of students' engagement in a school's makerspace

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Abstract

This study investigates the sociomaterial movements of student engagement in a school's makerspace. Here, we understand sociomaterial movements as emergent and relational, comprising complex dynamics of agency across students, teachers and materials in situated, culturally framed activities. Our study draws on data comprising 85 hours of video recordings of 9–12-year-old students' (N = 94) engagement in a technology-rich makerspace in a Finnish elementary school. The video data were transcribed and analyzed qualitatively using a multimodal interaction analysis. The sociomaterial movements were found to be displayed across a tension-laden continuum between (1) procedural activity—analysis and reflection; (2) individual activity—collaboration; (3) "doing school"—empowerment; and d) alienation—identification. Together, the study offers a potential approach for investigating and understanding the often overlooked workings of sociomateriality that constitutes students' emergent engagement and learning opportunities in science, technology, engineering and mathematics (STEAM) learning contexts.

Introduction

Recent technological developments have resulted in major reconfigurations to the materialities of educational settings. As a result, several researchers have called for a more nuanced conceptualization and empirical operationalization of the material relations emerging in novel technological infrastructures and technology-rich learning environments (eg, Fenwick & Landri, 2012; Hetherington & Wegerif, 2018; Kumpulainen, Rajala, & Kajamaa, 2019). In the current study, we respond to these calls and consider how the key tenets stemming from sociomaterial theorizing (Barad, 2003, 2007; Orlikowski, 2007; Orlikowski & Scott, 2008) can contribute to understanding the often overlooked workings of sociomateriality in science, technology, engineering and mathematics (STEAM) learning contexts, namely makerspaces.

Practitioner notes

What is already known about this topic

- Makerspaces prescribe learner-centered pedagogies in which students work on science, technology, engineering, arts and mathematics (STEAM) design projects.
- Research points to qualitatively novel relationalities among students, teachers and materials in makerspaces.
- The existing research calls for further investigation of the educational quality, inclusivity and equity in makerspaces.

What this paper adds

- Shows how the application of sociomaterial theorizing can inform the study of complex relational dynamics of agency in a school's makerspace.
- Introduces "sociomaterial movement" as a potential conceptual heuristic to research and understand emergent, relational and tension-laden intra-actions among students, teachers and materials in situated, culturally framed activities in a makerspace.
- Demonstrates how the educational potential of makerspaces depends on the sociomaterial forces at work.

Implications for practice and policy

- Moves beyond more traditional studies of agency–structure dynamics by unpacking the often overlooked workings of sociomateriality in makerspaces.
- Furthers the development of maker pedagogies that recognize the complex dynamics of sociomateriality.
- Contributes to the further design of makerspaces and their technological infrastructures.

Makerspaces draw on learner-centered pedagogies in which students can ideally engage in personally meaningful STEAM design projects, while simultaneously navigating several fields of knowledge and using novel technological tools such as 3D printers, electronics, programming software and digital applications (Halverson & Sheridan, 2014; Honey & Kanter, 2013). Research has shown how engaging in makerspaces enhances students' creativity and imagination (Burke & Crocker, 2019), design thinking (Hughes, Morrison, Kajamaa, & Kumpulainen, 2019), transformative agency (Kajamaa & Kumpulainen, 2019) and learning in STEAM subject areas (Bevan *et al.*, 2016). Makerspaces are also suggested as a way to enhance students' interest-driven engagement in STEAM learning, as well their development of transversal competencies, including collaboration and creative and critical problem-solving (Blum-Ross, Kumpulainen, & Marsh, 2019; Peppler, Halverson, & Kafai, 2016; Sheridan *et al.*, 2014).

At the same time, the existing research on makerspaces has identified critical features requiring further investigation. For instance, makerspaces have been criticized for their narrowly defined goals and consequent failure to attract and engage a broader population of young people (Blikstein & Worsley, 2016). Earlier research has also shown how teacher intervention in the students' activities in makerspaces creates different learning opportunities (Kajamaa, Kumpulainen, & Olkinuora, 2020) and how the educational potential of makerspaces is entangled with the cultural, social and material forces at play (Kumpulainen *et al.*, 2019). In all, the existing research urges further investigation into makerspaces' ability to create equitable and deep learning experiences for all students.

In our study, we address these research needs by investigating the sociomaterial movements of students' engagement in a makerspace, where sociomateriality refers to the constitutive entanglement of the cultural, social and material in students' everyday participation in makerspaces (Barad, 2003, 2007; Orlikowski & Scott, 2008). We understand sociomaterial movements as emergent and relational, comprising the complex relational dynamics of agency among students, teachers and materials in situated, culturally framed activities. We hold that a sociomaterial view is well suited for our purposes given its focus on interdependencies among multiple agents in the organization of an activity. A sociomaterial approach allows us to focus on the emergent, complex and entangled forces of agency in a school's makerspace, contributing to the existing literature on the educational potential of makerspaces. Our study moves beyond more traditional studies of agency–structure dynamics that typically position human agency over the material with less attention to the sociomaterial entanglements of activity. Therefore, in our study, we ask the following questions: How do the sociomaterial movements of the students' engagement represent themselves in a school's makerspace? What commonalities, tensions and boundaries exist between the identified sociomaterial movements? How do the dynamics of agency across the students, teachers and the material play out in the identified sociomaterial movements?

Theorizing sociomaterial movement

Following sociomaterial theorizing, we treat matter and meaning not as separate but as an entangled reality in which humans and materials intra-act to impact the activity and its outcomes (Barad, 2003, 2007; Fenwick & Landri, 2012; Orlikowski, 2007; Orlikowski & Scott, 2008). We hold that the intra-actions to which both people and materials contribute co-create sociomaterial movements that have consequences for students' engagement and learning opportunities, as well as educational change (Kumpulainen, Rajala, & Kajamaa, 2019). Consequently, makerspaces account for the sociomaterial space of possibilities in which humans and materials intra-act and together perform particular learning actions. Further, there are no presupposed subjects or objects because agency is distributed and matter only matters in its intra-active becoming (Barad, 2003). Accordingly, individual actions are regarded as intersecting with the social and material, with all agents acting in varied roles and meanings with unforeseen outcomes. It is these sociomaterial movements that our research aims to examine.

Our sociomaterial view holds that agency is constantly in flux and moving and is generated through a range of elements within environmental assemblages. Hence, we move beyond viewing agency as a property of individual human actors. Rather, agency is seen as coproduced in complex relations among various materials, between humans and materials and among humans (Bennett, 2010). Our approach also extends the more traditional understanding of the role of materials as mediational means (Vygotsky, 1978) by emphasizing the generation of novelty in every action that cannot be traced back to distinct individual or collective human intentions; rather, "the universe is agential intra-activity in its becoming" (Barad, 2003, p. 18). On this basis, our study brings attention to the dynamic, messy and open-ended character of student sociomaterial movements and agency in a makerspace context.

In this study, we view and analyze the social and material as constitutively entangled in students' engagement in makerspaces (Orlikowski & Scott, 2008). Namely, our interest lies in what happens and is produced when different agents intra-act in a school's makerspace. In following Orlikowski (2007), our approach holds that the distinction of humans and material can only be analytic because in reality, humans and their activities are constituted through relations of materiality; indeed, there are no independently existing entities. Further, we explore the complex dynamics of sociomaterial movements of students' engagement in a school's makerspace through the logic of tension and opposition between sociomaterial and organizational forces. We hold that the forces of tension and opposition underlying sociomaterial movements in a school's makerspace are connected to the historical development and transformation of educational practices. For example, our earlier research suggests a tension-laden dynamic between the traditional ways of schooling and student-driven creative STEAM design activities in school-based makerspaces (Kumpulainen, Kajamaa, & Rajala, 2018).

Study

Research setting

The context of our study is a city-run comprehensive elementary school. The students come to school from the local catchment area and represent diverse socioeconomic and cultural backgrounds. The school strives for student-centeredness and design thinking across the curriculum. In 2016, the school introduced the FUSE Studio makerspace (www.fusestudio.net) into its educational program as one of its elective courses for students in Grades 4–6. The FUSE Studio is situated in the school's computer lab, a neighboring classroom space and the nearby hallway. The computer lab contains 22 desktop computers and separate laptops.

The FUSE Studio

The FUSE Studio introduces students to different design challenges, including robotics, game design, electronics and graphic design (Stevens & Jona, 2017; Stevens *et al.*, 2016). Each challenge is designed to engage students in different STEAM topics, skill sets and learning goals. The challenges are accompanied by computers, 3D printers and other materials, as well as instructions on how to process the challenges (Stevens & Jona, 2017; Stevens *et al.*, 2016). Some of the challenges are fully digital, and in some challenges, the students can use other materials that are provided to them in separate kits. Students' progression in their activities and learning is documented through photos and videos (Stevens & Jona, 2017). The students can access the challenges and their instructions through a website. On this website, the students can watch trailers of each FUSE challenge. Based on the trailers, the students can choose the challenge that is the most appealing to them. They can then access the challenge's instructions, which include both written instructions and video tutorials.

According to the developers of the FUSE Studio (eg, Stevens & Jona, 2017), three main lines of research affected its development. First, the designers wanted to invent an alternative, interest-driven way for students to participate in STEM learning through arts and design (ie, STEAM). Second, the designers wanted to enhance connected, peer-based learning that could result in relative expertise, ie, students developing expertise relative to each other through peer collaboration. According to the developers, teachers need to take a new role in the FUSE Studio to facilitate students' peer collaboration and relative expertise instead of instructing them (Stevens & Jona, 2017). Third, the FUSE Studio benefits from video game design principles by introducing students to challenges that level up in difficulty. This is expected to promote students' voluntary and persistent engagement (Stevens & Jona, 2017). In our study, we examine how the sociomaterial movements of the students' activity are in line with the design principles of the FUSE Studio makerspace and its educational goals; thus, we direct our attention to the emergent nature of the students' maker activity in situ.

Participants

Our data derive from three groups of students who chose the FUSE Studio as an elective course for the academic year 2016–17; Group 1 consisted of 32 fourth graders (22 boys and 10 girls), Group 2 of 30 fifth graders (19 boys and 11 girls) and Group 3 of 32 sixth graders (19 boys and

13 girls). Each group had one 45–60-minutes FUSE session a week. Two to four teachers and teaching assistants supported the students during each session.

Data collection

We collected the data through videoing the students' and teachers' activities in the FUSE Studio. From August to December 2016, the data collection took place once a week for each of the three groups. Five researchers took responsibility for the video data collection using four mobile cameras. The recording of each session lasted from 45 to 60 minutes. Usually, two of the cameras followed the teachers, and two were set to record the students' activities. The researchers decided on the students and teachers that they videoed throughout each session. The main principle that guided the decisions regarding the focus of the cameras for each session was motivated by the need to form a comprehensive picture of the nature of interactions and activities in the FUSE Studio. To support the data collection, we produced an Excel spreadsheet that identified the students, teachers and the FUSE challenges that the students' chose to work on each session. The spreadsheets guided the focus of the video cameras for the next session and later supported the analysis of the collected video data. Altogether, the data corpus of the study consists of 85 hours of video records. Capturing all the activities and interactions was a challenging endeavor because of the movements of students, student groups, teachers and materials in the makerspace. Therefore, we understand the limitations of our study in documenting the complexity of ongoing activities through the chosen means.

Data analysis

Our analysis followed multimodal interaction analysis (Kress, 2010; Streeck, Goodwin, & LeBaron, 2011; Taylor, 2014), taking into account the students' verbal expressions, the paralinguistic channels of their communication (eg, intonation, cutoffs, sound stretches), their body postures and movements (eg, head movements, standing up, postural shifts), their facial expressions and gaze, their turn-taking patterns and the temporal coordination of their gestures and talk, along with the handling of the materials.

The video data of this study have been analyzed with Atlas.ti software by four researchers. Our unit of analysis is "a meaningful unit of activity" with a detectable beginning and ending. Typically, the analytic unit was considered to begin when a new activity was initiated, such as when a student or teacher joined in the maker work either through their own initiation or in response to a request by the student(s) or teacher(s). We considered an analytic unit to have ended when the nature and/or focus of the ongoing activity clearly changed, such as when the teacher(s) or student(s) withdrew from an ongoing activity or changed the FUSE challenge they were working on.

Our analysis proceeded through three sequential phases. The first phase was descriptive and was motivated by the need to understand the various ways in which the sociomaterial movements displayed themselves in the makerspace. In practice, our analysis meant a close reading of the whole ethnographic video data to identify the commonalities and differences in the students' activity that could be used as the basis for categorization. We also constantly compared our data-driven interpretations with the design principles of the FUSE Studio and with the research literature on the educational goals of makerspaces, situating our analysis within an abductive approach (Dey, 2003). In our analysis, we were particularly interested to investigate how the sociomaterial forces at play produced educationally intended and/or unintended activity among the students. Through close reading of the video data and discussions in our research group of the saturation of our emerging findings, we ended up analyzing more closely 187 analytic units from the whole data set, accounting altogether for 5 hours and 40 minutes.

In the second phase of our analysis, we conducted purposeful sampling (Patton, 2002) of the identified sociomaterial movements to identify commonalities, tensions and boundaries among them. This resulted in our categorization of four opposing forces in the identified sociomaterial movements in the school's makerspace: (1) procedural action—analysis and reflection; (2) individual activity—collaboration; (3) "doing school"—empowerment; and (4) alienation—identification.

The third and last phase of our analysis was interpretative and was motivated by the goal to understand the reasons for our findings, ie, why the phenomenon came about (Elliott & Timulak, 2005). In this phase, we were interested in the dynamics of agency between the students, teachers, and materials and how these played out in the identified sociomaterial movements and opposing forces among them. Through our analysis we wanted to unpack the nuanced entanglements of agency that produced different sociomaterial movements in the students' maker activity. Our analysis hence makes visible the sociomaterial forces at play that account for the nature of the students' emergent engagement and learning opportunities in the makerspace.

Results

In this section, we illuminate our findings using representative empirical examples from the data. Our results make visible the ways in which the sociomaterial movements represented themselves in the data. We also unpack the dynamics of agency across the students, teachers and materials in the identified sociomaterial movements as a way to understand their workings in and for the students' engagement and learning opportunities.

Sociomaterial movements between procedural action and analysis and reflection

Our findings make visible the sociomaterial movements that produced the students' procedural action and analysis and reflection. In procedural action, the instructions and procedures of the FUSE Studio makerspace or those of the teacher often took agency over the students' maker activity, whereas analysis and reflection represented students' agentic actions. Altogether, our analysis reveals a strong dominance of the students' procedural activity over analytic and reflective activity in the FUSE Studio makerspace.

Table 1 shows how a FUSE challenge called Solar Roller turned out to be difficult for the students to grasp because of the complexity of the instructions, which contributed to the students' procedural activity—and in this case as well, frustration—with the material dimension of agency taking over the activity. We can also see the importance of the teacher in helping the students in proceeding in their work. However, the way in which the teacher supported the students did not encourage their own analysis and reflection of the activity but instead encouraged the procedural activity. Here, the teacher's interactions were also in tension with the design principles of the FUSE Studio, which views teachers as facilitators rather than instructors.

In contrast, we identified sociomaterial movements in other situations, here manifesting in the students' analytic and reflective engagement. In our example, the students were critically and reflectively exchanging ideas and questioning each other while working on a FUSE challenge called Jewelry Designer. This challenge involved designing one's own jewelry and printing it with a 3D printer. Here, the students showed excitement, and the discussion had a positive and constructive tone. The students were exchanging different design ideas for their jewelry through verbal and written accounts and building on one another's ideas, comments and actions. The students were also comparing the FUSE Studio instructions for the challenge against their own design ideas and drawing with paper and pencil to explain what they mean. Clearly, the students' sense of connection and ownership over the Jewelry Designer challenge contributed to the

Table 1: Procedural action—Analysis and reflection

Example	*Procedural action*	*Analysis and reflection*
Where and who	Four students (females) are working together in a classroom with a maker challenge	Four students (females) are working together in a classroom with a maker challenge
Participants	Emmi (fuzzy grey cardigan), Silja (hoodie), Nellie (black t-shirt with white text), Una (grey t-shirt with black text)	Silja (black hoodie), Nellie (white t-shirt and grey cardigan), Emmi (white shirt), Una (fuzzy white pullover)
Maker challenge	Solar Roller: Get a vehicle moving using solar energy	Jewelry Designer: design your own jewelry (eg, earrings, necklaces) and print it in 3D
Illustrative picture of the situation		
Nature of interaction	The students are mainly expressing themselves verbally, but the space and its materials are essential parts of their communication	The students' interactions have seemingly multimodal dimensions because both gestural movements and drawing on paper are used as part of communication.
Description of the activity	Nellie, Una and Silja are standing around a table with the materials for the challenge. Emmi is sitting nearby at a desk working on a laptop. Nellie, Una and Silja are discussing what materials they will need. Emmi gets up and walks over to the others, intervening with comments about the FUSE instructions, which she has just been reading on the laptop. Emmi expresses that she has trouble understanding the instructions, and she walks back to the laptop. The other students continue examining the materials. After a while, Emmi calls out to the other students, expressing frustration with the instructions. The students are now moving between the laptop and the table with the materials. They are confused about the materials and instructions. After a while, they ask for help from a teacher, who sits down and explains the instructions to them. The teacher instructs them on what to do and how to connect the different parts. When the teacher leaves the situation, the students begin connecting the parts according to the teacher's advice	The students are exchanging ideas about what sorts of earrings they could design. Nellie explains that she wants to make earrings that resemble the Adidas logo. Una questions this idea by commenting that, according to the challenge instructions, the design should be simple. Emmi builds on Una's statement and explains that the design should be based on a square form and should not have too many extra details. Nellie says something inaudible and then says that three lines are not much. Emmi shows excitement, as if she has had an idea; she explains that one design could be "a dangling earring", with three white stripes dangling from the ear. Nellie says "ooh," waves her arms, and says that she now knows what design she wants to make. Emmi draws on her paper and continues to explain how the earring with the stripes would look. The students then continue to explain and compare different design ideas with one another. At this point, they also draw examples of their ideas and show them to each other

nature of their analytic and reflective engagement, evidencing the students' agentic actions in the makerspace.

Sociomaterial movements between individual activity and collaboration

Our study makes visible how the students' engagement dynamically moved between and across individual and collaborative working modes. Notably, the nature of the FUSE challenge the students chose to work on encouraged either individual or collaborative working modes. For instance, maker challenges that were realized through computers encouraged individual work, and those that involved handling and building with physical manipulatives lead to collaboration among the students (see also Kumpulainen *et al.*, 2019). Hence, our study shows how the material, ie, the FUSE challenge, influenced the students' way of working either alone or in collaboration with others.

Table 2 describes two examples from the students' work on the Jewelry Designer challenge, with each student working on her own challenge with a laptop to design her own jewelry. As our examples show, the students indicated a preference to work alone on this maker challenge. However, we can also detect collaborative modes of engagement even if the students were working on their own challenges. Usually, in these situations, collaborative activity emerged when the students needed help from one another or when they found each other's work interesting so that they wanted to join in. We could identify occasions during which the students helped one another, moving from one laptop to another and discussing their work. It was in these dynamic and shifting intra-actions among the students, space and materials when the relational expertise advocated by the designers of the FUSE Studio became visible.

Sociomaterial movements between "doing school" and empowerment

Our study reveals sociomaterial movements in the students' engagement in the school's makerspace between the opposing forces of "doing school" and empowerment. By "doing school," we refer to activity that indicates the students fulfilling the expectations of the school with little personal interest or commitment. Our study shows how there was a constant interplay between "doing school" and empowerment in the students' activity in the school's makerspace.

As shown in Table 3, the students were working on a Solar Roller FUSE challenge: a design activity inviting the students to build a car that functions with solar energy (a lamp and solar panel). For these students, the goal seemed to be to finish as fast as they could and to keep up with others. One of the students (Emmi) also seemed very focused on the requirements for the maker challenge and the correct way to finish it, seeing the instructions as the absolute rules from which one should not diverge. Emmi also expressed stress about performing well and a fear of failure, comparing her own group's progress to that of other groups. It is clear from this example how the institutional context of the school, its rules and conventions materialized themselves as emergent in the students' engagement in the makerspace, creating a tension between the design principles of the FUSE Studio makerspace that favors students' agency and empowerment.

In contrast, in the other example in Table 3, we witnessed empowerment because the students could follow their own interests and passions, which at times also deviated from the FUSE Studio challenges. Here, the students demonstrated personal commitment towards the activity and a willingness to work with even more difficult challenges than originally expected to accommodate their interests and make the activities meaningful for them. These modes of activity and participation structures resonate more closely with the design principles of the FUSE Studio. In the following example, the students were working together on the Keychain Customizer challenge, and they decided to design a keychain with their full names rather than using their initials (as

Table 2: Individual activity—Collaboration

Example	*Individual activity*	*Collaboration*
Where and who	Five students (females) are working together in a classroom with a maker challenge	Five students (females) are working together in a classroom with a maker challenge
Participants	Silja (light-coloured shirt), Nellie (black hoodie with white text, ponytail), Emmi (black hoodie with white text), Una (grey shirt), Heidi (white pullover with blue stripes)	Silja (light-coloured shirt), Nellie (black hoodie with white text, ponytail), Emmi (black hoodie with white text), Una (grey shirt), Heidi (white pullover with stripes)
Maker challenge	Jewelry Designer: design your own jewelry (eg, earrings, necklaces) and print it out in 3D	Jewelry Designer: design your own jewelry (eg, earrings, necklaces) and print it out in 3D
Illustrative picture of the situation		
Nature of interaction	The students communicate multimodally. Nellie is expressing herself verbally to Heidi, and Heidi is answering with body language and a “shhh” sound. Heidi is indicating to Nellie that her help is unwelcome at this moment	The students communicate multimodally. They engage in verbal explaining, but also show and demonstrate their points and ideas through their laptops
Description of the activity	Silja, Nellie, Emmi, Una and Heidi are sitting at their desks and are working individually. Each of them is using a laptop and its design software, and they are occasionally talking to one another. Heidi, who is sitting behind Nellie, has previously had some trouble with her laptop. Nellie is sitting turned towards Heidi and leaning towards Heidi’s desk, offering to help her and saying she knows what to do. Heidi is making a “shhh” sound and waving towards Nellie as if to try and get her to go away. Nellie continues to lean towards Heidi, insisting that she can help. Heidi slaps at Nellies cheek and Nellie slaps back at Heidi’s. This is done in a playful manner, but Heidi is clearly expressing a wish to work alone at this moment. Nellie then turns towards her own table and continues with her own work	Silja, Nellie, Emmi, Una, and Heidi are collaborating by helping and by discussing their work with one another. Heidi and Silja are sitting next to each other at a desk working on Silja’s design. Heidi is leaning over towards Silja’s laptop and using the mouse, making changes to Silja’s design. Silja observes what Heidi is doing on the laptop and gives comments about the design, while simultaneously demonstrating the size of the design with her right hand. Emmi is sitting at Una’s desk working on Una’s laptop. Una is sitting on a desk on the right side of Emmi, and Nellie is standing on the left side of Emmi. Una and Nellie observe Emmi’s actions on the laptop. They are discussing different options and manoeuvres in the design software. Emmi is demonstrating on the laptop and giving Una advice on how to use the software while they reflect together

Table 3: "Doing school"— Empowerment

Example	*"Doing school"*	*Empowerment*
Where and who	Four students (females) are working together on a maker challenge	Two students (males) are working together on a maker challenge
Participants	Emmi (fuzzy grey cardigan), Silja (hoodie), Nellie (black t-shirt with white text), Una (grey t-shirt with black text), and Pete (teacher)	Alex (black t-shirt), Lassi (long-sleeved shirt), Nils (teacher), and Pete (teacher)
Maker challenge	Solar Roller: Get a vehicle moving using solar energy	Keychain Customiser: Design and 3D print a keychain with your name or custom message
Illustrative picture of the situation		
Nature of interaction	A student, Emmi is expressing herself verbally, and the others are listening and giving short comments	The communication is mostly verbal and the teacher discusses the challenge with the students. The students and the teacher are focusing on the design on the laptop, looking and pointing at it while talking
Description of the activity	Emmi, Silja, Nellie, and Una are working on the Solar Roller challenge. The students are gathered around a table with a lamp and the car they have built. They are trying to get the car to move using the light from the lamp so that they can move to the next level of the challenge. Emmi is holding a solar panel under the light from the lamp. Emmi explains to the others that to finish the challenge, they still need to film the Solar Roller car when it is moving. Emmi is talking about how they, as a group, have fallen behind with this challenge and how the other groups are much further along. As Emmi is talking, she is looking over her shoulder around the FUSE Studio makerspace. She then states that they are only carrying out the second level of the challenge and did not succeed with the first level. This seems to bother Emmi, and she sounds and looks dissatisfied	Alex and Lassi are sitting at a desk, working together with the same laptop to design a keychain to include Lassi's name. During the design process, the students take turns working on the laptop. At the end of the process, Lassi is sitting at the laptop, and Alex is standing behind him, giving suggestions. They seem happy with their work, and Alex calls out to a nearby teacher (Nils), saying that they have finished the design. The teacher comes to the laptop and looks at the design. He asks the students if they have followed the instructions for the challenge carefully, suggesting that they have perhaps missed something essential. The teacher is referencing the students' choice to print Lassi's whole name on the keychain, even though the instructions say to include only the initials. Alex argues that the other teacher (Pete) has given them permission to deviate from the instructions. The teacher Nils goes and checks whether this is true with Pete. It turns out that Pete has agreed that the students can include their whole names if they print the design in a smaller size using the 3D printer

outlined in the challenge instructions). The teacher (Nils) questioned the students' creative and deviating actions, but one of the students (Alex) argued back, holding his ground and stating that they have permission to do the challenge differently. Here, we can witness students' agency leading the activity.

Sociomaterial movements between alienation and identification

Our study illustrates the sociomaterial movements of alienation and identification in the students' engagement in the FUSE Studio (see Table 4). Alienation typically manifested in situations during which the use of the technological tools of the FUSE Studio was experienced as difficult by the students and when they were not receiving help from their peers and/or teachers. Oftentimes, in these situations, the students demonstrated low motivation, which can be interpreted as both a result (ie, they were not interested in the maker activity to start with) and/or a consequence (ie, they became disinterested because of experienced difficulties) of alienation. In all, our study shows that the students' identification in their maker activity was more frequent compared to alienation.

In our example, which resulted in alienation, a student (Antti) was working on a FUSE challenge called Eye Candy that involves designing and printing one's own sunglasses. The student was struggling with both the practical issues of working in the FUSE Studio makerspace (signing in and finding and understanding instructions) and his own motivation. The teacher's advice and help pushed him forward in the process, but this did not seem to have had much effect on the student's interest in engaging in the maker work. This could indicate that the student had not gotten the kind of support or help he needed from his peers or teachers or that he did not find the maker work and challenges interesting. Finally, the student gave up and started playing a computer game irrelevant to the maker's activity.

In contrast, we observed the students' identification with the FUSE Studio makerspace and its activities. As demonstrated in our example, a student (Ilmari) described the Ringtones FUSE challenge as personally pleasing and creating music that is collectively celebrated by himself, his classmates, and the teacher. In this example, the student showed agency and a focused interest in the maker work, seemed to be pleased with the music he made, and was eager to play his music for others. The student (Ilmari) danced to his own music while playing it. The other students and the teacher also became excited about the music, expressing that it was good, and they all began smiling and dancing to the music. In this example, we can also see how the teacher recognized the student's talent and proposed a potential future career for him as a music maker. Altogether, the sociomaterial dynamics of agency among the students, the teacher, and materials created a fertile context for the students' strong identification with the maker activity in accordance with the design principles of the FUSE Studio.

Discussion and conclusions

Our study offers a novel approach to the study of sociomateriality in a school's makerspace; it speaks to the importance of moving beyond approaches that treat materiality as either invisible or inevitable or that separate technology from human affairs (Orlikowski, 2007). It also takes us beyond seeing agency as the property of an individual or as an interactional dynamic between agency and structure (Pickering, 1995). Our study provides insights into how both humans and materials operate within agentic assemblages and how practices and relations emerge. It shows how a notion of agency as exclusively about empowering students as having the opportunities to exercise choice and make decisions hides the complexity of the sociomateriality of makerspaces (Charteris & Smardon, 2018). Instead, our study shows how agency is not a property of the students, teachers nor materials but rather is an effect arising within relations, a mangling of

Table 4: Alienation—Identification

Example	*Alienation*	*Identification*
Where and who	Two students (males) are working individually on maker challenges on their computers next to each other	One student (male) is working on a maker challenge on a laptop in a classroom
Participants	Riku (dark shirt) and Antti (grey hoodie). Two teachers are also seen in the video: Santtu and Joonas	Ilmari (grey shirt), Nils (teacher), Aaro (grey hoodie), Benjamin and Anders (do not show in the picture)
Maker challenge	Eye Candy: Design and print your own sunglasses	Ringtones: Produce your own music using professional audio mixing software
Illustrative picture of the situation		
Nature of interaction	The communication is multimodal. In addition to some verbal interaction, Riku's frustration and lack of motivation are realised by his body posture and facial expressions	The communication is multimodal. The students communicate their interests, compliments, and pleasure through verbal expressions, body postures and movement (eg, moving, with the music), facial expressions, and coordination of gesture and talk
Description of the activity	Antti and Riku have been working beside each other individually on separate computers during the whole session. They have occasionally briefly helped each other. Both have had trouble proceeding with their challenges, and both have experienced technical problems and problems understanding the instructions. The teachers occasionally helped them. For Antti, it has taken almost the whole session to get logged into the FUSE Studio and to choose a new challenge to start. Finally, he chooses the same challenge that Riku is working on. At the end of the session, Riku has managed to finish his challenge and is trying to save it. Antti is not yet finished and instead of continuing with the challenge departs from the FUSE challenge and starts playing a computer game. When Riku asks for help from the teacher in saving his design, the teacher notices that Antti is playing a game and orders him to close it. Antti closes the game and opens some other windows on the computer, looking over his shoulder	Ilmari is sitting at a desk and working individually with a laptop on the Ringtones challenge. Other students are also sitting at their desks, working individually or in small groups. The teacher (Nils) and Aaro walk over to Ilmari's desk and listen through the laptop to the music he has made. Ilmari then begins to dance, making the teacher (Nils) also dance. Aaro asks if Ilmari has made the music himself. Anders, who is sitting at a desk nearby, tells the teacher that Ilmari is really good at making music, and the teacher agrees. Nils continues dancing to Ilmari's music and asks if Ilmari has made music at home. Ilmari says "no" and the teacher suggests that he is talented and should keep making music. Benjamin comes over and sits down at the desk next to Ilmari. Benjamin starts dancing to Ilmari's music and smiles, and Ilmari and Nils also dance

human and material agencies (Pickering, 1995). Depending on what assemblage was analyzed, agency was observed a flowing between students, students and teachers, students and materials, students, materials and teachers, or among any combination of these. Hence, our study moves beyond the instrumental conceptions of students managing their engagement and learning in makerspaces to the recognition of the sociomaterial dynamics of agency. The analysis of agency, from this point of view, required close attention to where and how, between whom, between what points, according to what processes, and with what effects agency was produced and enacted. Further, our study demonstrates that there is not necessarily a causal link between a new learning space, such as a makerspace and educational change, because change is the result of multiple sets of relations and agency (Mulcahy, Cleveland, & Aberton, 2015). In all, our study shows that an enlarged conception of agency that that takes account of the emergent sociomaterial forces agency provides a richer conception of educational opportunity than one that focuses exclusively on student agency or agency–structure dynamics (Charteris & Smardon, 2018).

Through our investigation, we revealed multiple, shifting and tension-laden sociomaterial movements that constituted student engagement and learning opportunities in the makerspace. The sociomaterial movements of the students' engagement in the school's makerspace were found to display themselves across a tension-laden continuum among (1) procedural action—analysis and reflection; (2) individual activity—collaboration; (3) "doing school"—empowerment; and (4) alienation—identification. These movements emerged from the complex dynamics of agency among the students, teachers and materials in situated, culturally framed activities.

In our study, we witnessed sociomaterial movements in the makerspace that resulted in less typical forms of student engagement in the institutional context of the school. Specifically, we identified interest-driven, collaborative and empowering engagement, evidencing relative expertise and the students' strong identification with their activity. These sociomaterial movements reconfigured more traditional student and teacher roles, the boundaries of expertise and physical spaces in which the students worked and the tools and materials they used within institutional conditions. In all, the nature of the students' engagement resonated with the design principles and educational goals of the FUSE Studio makerspace (see Stevens & Jona, 2017).

At the same time, we identified sociomaterial movements in the makespace that resulted in more typical school practices. At times, the teachers also emphasized and maintained the more established and traditional organization of the school through their authoritative and instructional interactions, leaving little space for the students' agency. These findings show how changing from the traditional role of the teacher, which is typically characterized by the transmission of knowledge and controlling students' activities, to becoming a facilitator of student-driven engagement and learning is not easy or straightforward (Kajamaa *et al.*, 2020).

Our findings make visible the performativity of the FUSE Studio makerspace as a creative sociomaterial assemblage (Suchman, 2007) that is shaped by the particular contingent way in which it is designed, configured and engaged in practice. Further, the study shows how the agency of the instructional designers of the FUSE Studio, the agency of teachers as implementers and supporters of the students' engagement in the makerspace, the agency of the technology and materials, the agency of the institutional structures and rules, and the agency of the students themselves all contributed to the students' engagement and everyday organization of activity, in general. Through our findings, we can see that it is not a matter of technology interacting with the social, but rather that it is constitutive entanglement, bringing together the students, teachers and the materials in intra-action in the cultural context of the school, creating emergent, shifting and tension-laden opportunities for engagement and learning. These findings evidence the value of the sociomaterial approach from more traditional studies of agency–structure dynamics that typically do not recognize such complex entanglements between humans and materials.

Our study demonstrates how the sociomaterial approach offers a useful lens to grasp the opposing forces of sociomaterial movements in students' engagement in a makerspace, generating valuable insights into the educational possibilities and tensions of makerspaces. The depiction of tensions and how agency plays out in these allows for a more nuanced understanding of the complexity involved in the fusion of human interactions and technology, showing them as being mutually dependent ensembles that constitute emergent practices in technologically rich settings (Orlikowski & Scott, 2008), such as a school's makerspace. We hold that analyzing sociomaterial movements and their opposing forces is important for understanding the complex and nuanced sociomaterial entanglements of students' engagement and learning opportunities in makerspaces, developing pedagogical practices and enhancing the educational potential of makerspaces and their technological infrastructures.

Acknowledging the limitations of our study in the data collection and analysis, coupled with our emerging understanding of the working of sociomateriality in makerspaces, we hold that there is a need for further research informed by the sociomaterial approach. Future research needs to investigate the constitutive entanglements of agency and students' engagement and learning opportunities in diverse makerspace settings (eg, in libraries, museums and schools) and in different material and disciplinary contexts. We also welcome a continued analysis over longer time periods to understand how sociomaterial movements develop and change over time in technology-rich STEAM learning environments across students, teachers and materials.

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Statements on open data, ethics and conflicts of interest

We do not have ethics approval to make the raw data from the current study available for sharing.

The study follows the ethical standards of scientific research established by the Finnish Advisory Board on Research on Integrity. Informed consent was obtained from all adult and youth participants and youth guardians. Pseudonyms were used for all individuals.

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